

BRIGHT lights, BIG city: Massive galaxies, giant Ly- α nebulae, and proto-clusters

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ABSTRACT

High redshift radio galaxies are great cosmological tools for pinpointing the most massive objects in the early Universe: massive forming galaxies, active super-massive black holes and proto-clusters. We report on deep narrow-band imaging and spectroscopic observations of several $z > 2$ radio galaxy fields to investigate the nature of giant Ly- α nebulae centered on the galaxies and to search for over-dense regions around them. We discuss the possible implications for our understanding of the formation and evolution of massive galaxies and galaxy clusters.

Keywords: High redshift, radio galaxies, massive galaxies, proto-clusters, black holes

1. RADIO SOURCES AS COSMOLOGICAL PROBES

High redshift radio galaxies (HzRGs; $z > 2$) are great beacons for pinpointing the most massive objects in the early universe, whether these are galaxies, black holes or even clusters of galaxies. At *low* redshifts powerful, non-thermal radio sources are uniquely associated with massive ellipticals. Their twin-jet, double-lobe morphologies and large luminosities suggested already early on that such galaxies must also have spinning, super-massive black holes (SMBH's) in their centers.^{?,?} We now know that the masses of the stellar bulges of galaxies and their central black holes are correlated,^{?,?,?} suggesting a causal connection. If radio sources are powered by SMBH's then it is no longer a surprise that their parent galaxies occupy the upper end of the galaxy mass function.

There is excellent evidence that radio galaxies are also the most massive systems at *high* redshifts, even though their parent galaxies are very young and may still be forming. The combined near-infrared 'Hubble' $K - z$ relation for radio and field galaxies[?] shows that HzRGs are among the most luminous systems at any given epoch up to $z \sim 5$. Between $0 < z < 2.5$ this $K - z$ diagram can be modeled using passive evolution of

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$5L_*$ ellipticals[?] which formed at $5 < z < 10$. Other evidence includes the direct detection of absorption lines from massive young stars,[?] large ($\sim 50 - 70$ kpc), multi-component rest-frame UV and optical morphologies,[?] the 'hyper' luminous rest-frame far-infrared luminosities ($L_{FIR} \gtrsim 10^{13} L_\odot$) and huge implied star formation rates^{?,?} ($\gtrsim 2000 M_\odot \text{ yr}^{-1}$), and last but not least, the very extended ($\sim 30 - 50$ kpc) molecular gas and dust clouds that have recently been discovered^{?,?} around several HzRGs showing that the star formation occurs on galaxy wide scales.

HzRGs are also excellent tools for finding over-dense regions ('proto-clusters') at high redshift. This is because, in standard Cold Dark Matter (CDM) scenarios, galaxy formation is a highly 'biased' process: the most massive galaxies, and the largest clusters of galaxies, are expected to emerge from regions with the largest over-densities.[?] Simply put: the most massive systems (galaxies, SMBH's and galaxy clusters) hang out together, and radio sources are a great way to find them and to investigate their interrelations and evolution.

In this paper we report on deep narrow-band imaging and spectroscopic observations of several $z > 2$ radio galaxy fields using the Keck and ESO/VLT telescopes to investigate the nature of giant Ly- α nebulae centered on the galaxies and to search for over-dense regions around them. We discuss the possible implications for our understanding of the formation and evolution of massive galaxies and galaxy clusters. We will adopt the cosmological parameters $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, for which the age of the Universe at $z \sim 2, 3$ and 4 is $3.5, 2.3$ and 1.6 Gyr respectively, and the angular-to-linear transformations are $9.0, 8.3$ and $7.5 \text{ kpc arcsec}^{-1}$.

2. GIANT Ly α NEBULAE

Since the discovery of the first HzRGs it has been known that they are surrounded by large Ly α emission-line nebulae.^{?,?,?,?} Because the nebulae are centered on large, young galaxies they provide a unique opportunity to study how such galaxies form (accretion or merging?), and about AGN/starburst feedback and chemical enrichment during this process (heating or outflow?). We therefore observed the Ly α nebulae of several HzRGs and describe the results for two of them in detail below. A summary of the largest high redshift Ly α nebulae currently known is given in Table 1.

Table 1. Large, High Redshift Ly α Nebulae

Name	z	Size kpc \times kpc	Log(Ly- α) ^b erg s ⁻¹	Telescope	Reference
MRC 1138-262	2.156	150 \times 120	44.3	VLT 8-m	Ref. ?
Francis' Blob ^a	2.380	100 \times 30	43.9	CTIO 4-m	Ref. ?
Steidel Blobs ^a	3.09	140 \times 120	44.1	Palomar 5-m	Ref. ?
B2 0902+34	3.395	140 \times 100	44.8	Keck 10-m	Ref. ?
4C 1243+036 ^c	3.570	160 \times 50	44.0	ESO 4-m	Ref. ?
4C60.07	3.791	110 \times 60	45.1	Keck 10-m	Ref. ?
4C41.17	3.798	190 \times 130	45.2	Keck 10-m	Ref. ?
TN J1338-1942	4.102	150 \times 40	44.7	VLT 8-m	Ref. ?

^a Radio 'quiet'

^b Depends on surface brightness limit (larger telescopes detect larger Ly- α nebulae)

^c Maximum size determined from long slit spectroscopy, not imaging

2.1. 4C41.17 at $z = 3.798$

4C41.17 was imaged using a custom-made, high throughput interference filter with a 65 \AA bandpass centered at the redshifted Ly $\alpha = 5839 \text{ \AA}$ line with the Echellette Spectrograph and Imager[?] at the Cassegrain focus of the Keck II 10m telescope. The data were obtained during photometric conditions and good seeing (FWHM = $0.57''$). With a total exposure time of 27,600s this Ly α image is the most sensitive obtained to date and reaches

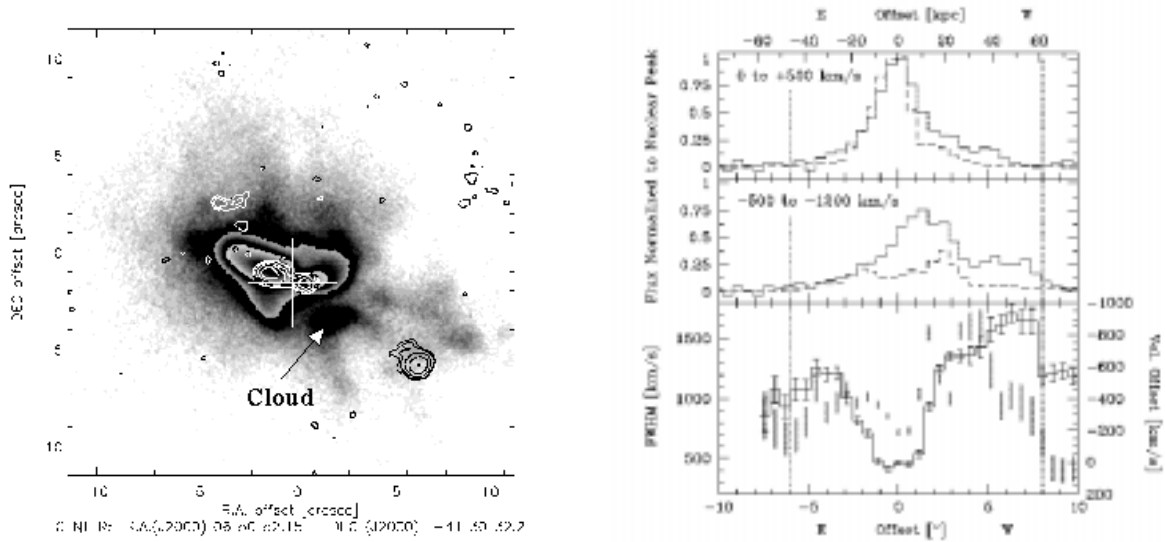


Figure 1. [Left] Keck narrow-band $\text{Ly}\alpha$ image (grey scale) of 4C41.17 overlaid with a 6 cm VLA radio image (contours).[?] The cross shows the position of the radio core. [Right] Normalized surface brightness profiles of the [OII] (solid) and $\text{Ly}\alpha$ (dashed) emission along the inner radio axis and the long south-west filament. Top: Extended [OII] in the velocity range 0 to +500 km s^{-1} . The spatial zero-point corresponds to the position of the radio core. Middle: Similar to top panel but for the velocity range -500 to -1200 km s^{-1} (Note: The 0 to -500 km s^{-1} range for [OII] is affected by near-infrared sky lines and is not shown). Bottom: Relative velocity (solid line) and velocity dispersion (bars) of the $\text{Ly}\alpha$ emission. Bar and symbol size indicate the respective uncertainties in the individual measurements. The projected distances of the south-west and north-east radio lobes along the slit direction are indicated (dotted lines).

a surface brightness of $8.0 \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ (3σ limit in a $2.0''$ diameter aperture). A broad-band R image, obtained as part of a multi-band spectral energy distribution study of the 4C41.17 field was scaled and subtracted from the $\text{Ly}\alpha$ image to construct the pure emission-line image shown in Figure 1. With linear dimensions of $190 \text{ kpc} \times 130 \text{ kpc}$ at the detection limit the 4C41.17 nebula is the largest presently known (Table 1).

A striking morphological feature of the nebula is a cone-shaped structure emanating from the center of the galaxy, with a 75 kpc long radial filament in the vicinity of the south-west radio lobe and a crescent-shaped cloud with radial horns. This morphology resembles that of other, nearby active and starburst galaxies and is suggestive of entrainment by the radio source,[?] outflow driven by radiative pressure from the AGN,[?] or a starburst superwind.[?]

Since $\text{Ly}\alpha$ is a resonance line, it is important to determine whether the nebula is ionized, or rather, results from the scattering of the $\text{Ly}\alpha$ photons (produced near the nucleus) by an extended neutral hydrogen gaseous halo. We therefore obtained a long-slit spectrum of 4C41.17 with the Keck II near-infrared spectrograph[?] (NIRSPE) to measure the extent and kinematics of other lines, [O II] $\lambda 3727$ and [O III] $\lambda 5007$, along the brightest filament of the $\text{Ly}\alpha$ nebula. We discovered both extended [OII] and [OIII] emission. In particular, [OII] emission was detected as far as $\sim 60 \text{ kpc}$ from the nucleus (Fig. 1). This shows that the $\text{Ly}\alpha$ nebula, at least in this direction, is not due to scattering but must be locally ionized. Furthermore, the presence of the emission lines of oxygen shows that the halo gas is not chemically pristine (primordial H, He) gas but has been enriched either at much earlier epochs (during the ‘Dark Ages’), or by more recent star formation.

The near-infrared [OII] and optical $\text{Ly}\alpha$ kinematics show that both emission lines exhibit large blue-shifted

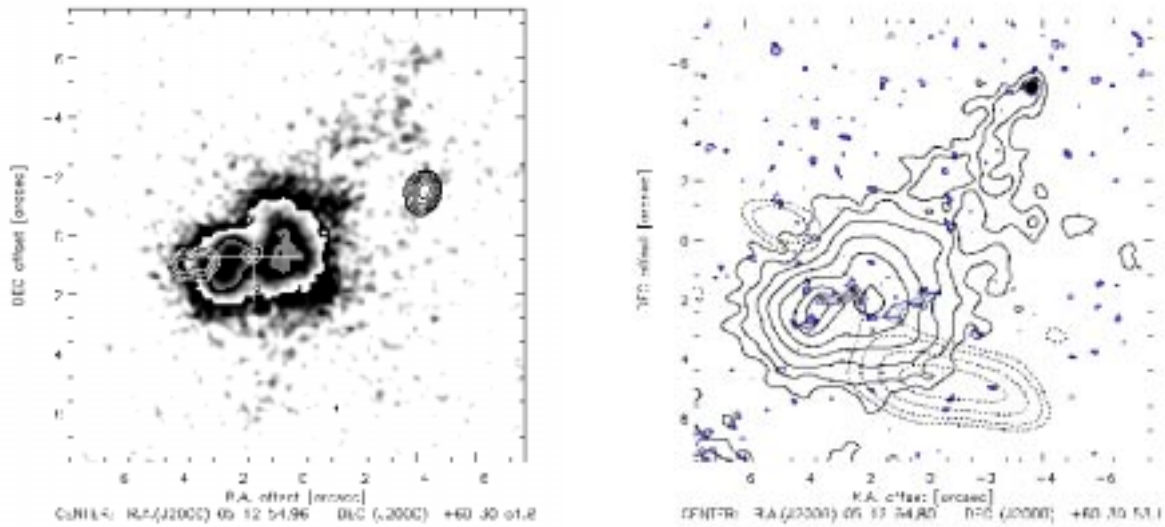


Figure 2. [Left] Keck narrow-band Ly α image[?] (grey scale) of 4C60.07 overlaid with a VLA radio image (contours) at 6 cm (contours). The cross shows the position of the radio core. [Right] HST ‘R’-band image of 4C60.07 (grey scale) overlaid with a Keck narrow-band Ly α image (contours) and IRAM interferometer dust image[?] (dotted lines).

velocities $\sim 600 - 900 \text{ km s}^{-1}$ (in projection) along the radio axis. In particular, the gas is very disturbed along the south-west filament, with Ly α velocity widths ranging up to $\Delta v_F \sim 900 - 1600 \text{ km s}^{-1}$. Beyond the radio hotspot, the velocity and velocity widths decrease abruptly. Evidence for entrainment of emission-line gas in long filaments, even if at considerable distance from the observed radio emission, has also been seen in nearby radio galaxies i.e., 4C29.30.[?]

We note that in the canonical picture of radio sources the hotspots and lobes are surrounded by bowshocks and cocoons of radio quiet, shock heated gas with a scale sizes which are significantly larger than the observed radio emission.^{?,?} In this picture the emission-line filaments located at the interface of the cocoons and the ambient gas and are not in direct contact with the radio lobes or hotspots and can even extend *beyond* radio hotspots[?] (Figs 1, 2), in particular if one also accounts for projection effects and the fact that the radio observations only show the highest surface brightness regions. The kinematics along the filament in 4C41.17, its radial filamentary structure, and the chemical enrichment of this gas therefore all indicate a process of entrainment of material away from the central regions by the radio source. The outer regions of Ly α nebulae may not have been affected by the sources, especially if they are still young and small, and one would expect these regions to be less enriched, as has been observed.^{?,?}

2.2. 4C60.07 at $z = 3.790$

Because of its very similar redshift the radio galaxy 4C60.07 could be observed with the same narrow-band filter as 4C41.17. The total observing time on source was 7,200s, resulting in a surface brightness detection limit of $\sim 2 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ (3σ limit in a $2.0''$ diameter aperture). Figure 2 shows the Ly α nebula in relationship to the radio source, rest-frame UV HST structure, and the extended dust and molecular gas that has been found in this system.^{?,?} Unfortunately the Ly α image is not as deep as for 4C41.17, not only because of the shorter integration time, but also because 4C60.07 has significant Galactic foreground extinction (~ 1.6 magnitude at the central wavelength of the narrow band filter).

Nevertheless one notes several similarities to 4C41.17 and other radio galaxy emission-line nebulae. First, the brightest Ly α emission is associated with the radio lobe which is closest to the AGN. This is presumably

because of asymmetries in gas density distribution, with denser gas providing more rampressure on the hotspots of the expanding radio source.[?] Second, the galaxy structure is very clumpy and approximately aligned with the radio source. This may be due to induced star formation by radio lobes which expand sideways into the cold, dense gas seen in the mm-maps. Good evidence for this has been found in 4C41.17.^{?,?} Third, and this is the first such evidence, the Ly α and dust/molecular gas emission show little overlap. We don't know how common this is since to date only three HzRGs have been imaged with mm interferometers with sufficient sensitivity to map their cold gas and dust emission and of these only 4C60.07 has a deep Ly α image. However, an anti-correlation between Ly α and cold gas certainly is not surprising given that Ly α is easily scattered and absorbed. In fact the overall impression is that the Ly α emission is more or less orthogonal to the dust and cold gas distribution, resembling M82 and its emission-line starburst superwind.[?]

2.3. Conclusions for Ly- α nebulae

Since many HzRGs seem to be surrounded by giant Ly α nebulae it seems likely that they play an important role in the formation of massive galaxies. What is the origin of this gas, what its fate?

With respect to the origin we should note that large Ly α nebulae also exist *without* central radio galaxies or AGN, and that these also show large velocity widths and gradients.^{?,?} In the absence of an obvious central source of ionization and/or outflow (but see Ref. ?) this suggests that Ly α nebulae are due to the accretion of primordial (?), cooling gas in large CDM halos.^{?,?} This gas provides a large reservoir of galaxies which supplies the building materials for galaxies forming at their centers.

As to the fate: Starburst[?] and AGN[?] outflows may eject accreting gas in forming galaxies when such outflows can overcome the galaxian potential, thereby limiting star formation and galaxy growth. This feedback mechanism may explain the fixed black hole to bulge mass ratios observed in nearby galaxies. In the case of HzRGs our data shows that this outflow may be significantly helped by shock heating and entrainment from the radio sources. We note that radio source induced 'hot bubbles' have also been invoked to reduce gas accretion in the centers of nearby cooling flow clusters, which seems required to explain X-ray observations.^{?,?}

Radio sources may be a significant source of heating and chemical enrichment during their life time[?] ($\sim 10^6 - 10^7$ yr). The cross sections of radio lobes are large[?]: tens of kpc² and much larger than the hotspots, which are only the highest surface brightness features that are visible in radio maps because of the steep radio lobe spectra and high restframe frequencies. The multiple component, asymmetric, and twisted radio structure of 4C41.17 and many other HzRGs suggests that the central SMBH may experience multiple periods of radio source activity and precession, presumably triggered by the interaction with one of the many clumpy components which make up the complex galaxy structure. If individual clumps move at radial velocities comparable to the velocity dispersion in the proto-clusters (~ 500 km s⁻¹, Table 2) and the closest are within ~ 10 kpc of the SMBH^{?,?} then it takes only $\sim 2 \times 10^7$ yrs to re-supply the AGN. The duty cycles for radio source activity could therefore be very short, at least during the period that the galaxies are being assembled. During this period a considerable fraction of the nebular gas would be heated and expelled. Not only could this then be the 'end of the beginning' for the galaxy, as its collapse gives way to mass ejection, it would also be the 'end of the beginning' for the proto-cluster as more and more metals are dispersed throughout the gas, stimulating cooling, star formation and galaxy evolution.

3. PROTO-CLUSTERS

Clusters of galaxies are convenient targets for studies of the formation and evolution of galaxies and may help constrain important cosmological parameters. Optical and near-IR surveys, assisted by X-ray selection, have found clusters^{?,?} out to $z \sim 1.3$. Very deep optical 'Lyman break' surveys have discovered galaxy over-densities ('proto-clusters') at $z \sim 3.09$.^{?,?} Such observations are time consuming and increasingly difficult at higher redshifts. They will not be able to provide substantial numbers of over-dense regions spread over a large range in redshift, which would be needed if one wishes to investigate how proto-clusters evolve, at what redshifts galaxy clusters become virialized, and what the cluster mass functions are.

Table 2. Proto-Clusters

Name	z	N_{NB}^a	N_{spec}^b	σ (km s $^{-1}$)	FOV c	Telescope	Reference
MRC 1138–262	2.156	51	15	280, 520	35	VLT 8m	Ref. ?
53W002	2.39	14	5	530	48	KPNO 4m	Ref. ?
MRC 0943–242	2.919	55	18	824	40	VLT + Keck	Ref. ?
SSA22a	3.09	72	10	400	77	Palomar 5m	Ref. ?
4C41.17	3.800	18	3	–	3.5	Keck 10m	Ref. ?
TN J1338–1942	4.102	28	20	325	40	VLT 8m	Ref. ?

a N_{NB} = Number of Ly- α excess candidates

b N_{spec} = Number of spectroscopically confirmed Ly- α galaxies

c FOV = field of view in sq.arcmin.

A practical way to identify proto-clusters is to search for over-dense regions around targeted objects. Radio sources are ideal for this since they are associated with the most massive galaxies and, in hierarchical CDM scenarios, therefore live in the most over-dense regions. Furthermore, radio selection is not biased towards dusty systems and provides an important alternative method to the optical/near-IR (rest-frame UV/optical) color selected searches.

The quickest way to identify potential over-dense regions around HzRGs is to use narrow-band filters, or better even, ‘tunable’ filters or other such imaging devices (Section 4) if they were available on the big telescopes. At least some fraction of the young galaxies in proto-clusters can be expected to be active starforming systems and such Ly α excess galaxies (LaEG’s) should be detectable in deep emission-line searches (Ly α at optical wavelengths for $z > 2$ objects). A deep narrow-band Ly α image of the $z = 3.09$ SSA22a proto-cluster field, which was initially found using broad-band color selection, confirmed this.[?]

Our Leiden, LLNL and ANU/AAO groups have undertaken a joint program of deep narrow-band and tunable filter imaging of HzRG fields with redshifts ranging between $2.2 < z < 5.2$ to identify proto-galaxy candidates through excess Ly α emission. This is then followed by multi-slit spectroscopy to confirm that their redshifts are close to that of the target HzRG. This method has been highly successful and we discuss two recent results in more detail below. A summary of presently confirmed proto-clusters is shown in Table 2.

3.1. MRC 0943–242 at $z = 2.919$

MRC 0943–242 was imaged using a narrow-band filter with a 68 Å bandpass centered at 4781 Å with the ESO 8.2m VLT Kueyen telescope using the imaging mode of the FOcal Reducer/low dispersion Spectrograph 2 (FORS2). The total exposure time was 22,500s, reaching a magnitude limit of $NB_{AB} = 26.7$ per (3σ , 2.0'' aperture) and the data were obtained during photometric conditions and 0.8'' seeing. A broad-band B image ($B_{AB} = 27.0$, 3σ , 2.0'' aperture) was used to identify Ly α excess galaxies in a manner as described in previous papers.^{?, ?} A total of 77 Ly α excess galaxy candidates were found above a limiting flux density of 5×10^{-18} erg s $^{-1}$ cm $^{-2}$ arcsec $^{-2}$ (3σ ; Fig 3).

We subsequently obtained multi-slit spectra of 24 of the LaEG candidates with the upgraded dual beam Low Resolution Imaging Spectrograph[?] at the Keck I 10m telescope. Two separate multi-slit masks were used, with total exposure times of 10,800s for each. We confirmed that 18 of the 24 galaxies were at the redshift of the radio galaxy. A histogram of the relative velocities and their spatial distribution is shown in Figure 3. The velocity dispersion is large (~ 824 km s $^{-1}$) with a hint of kinematic substructure at ~ 1000 km s $^{-1}$ blueward of the radio galaxy. A bimodal velocity distribution has also been found in the $z = 2.156$ HzRG proto-cluster around MRC 1138–262 (Table 2), and is fairly common even in much lower redshift galaxy clusters. The spatial distribution shows possible evidence for substructure as well, with small groups of 4 - 6 LaEGs to the West and South of the radio galaxy. More spectroscopic observations of the remaining LaEG candidates are planned to investigate this.

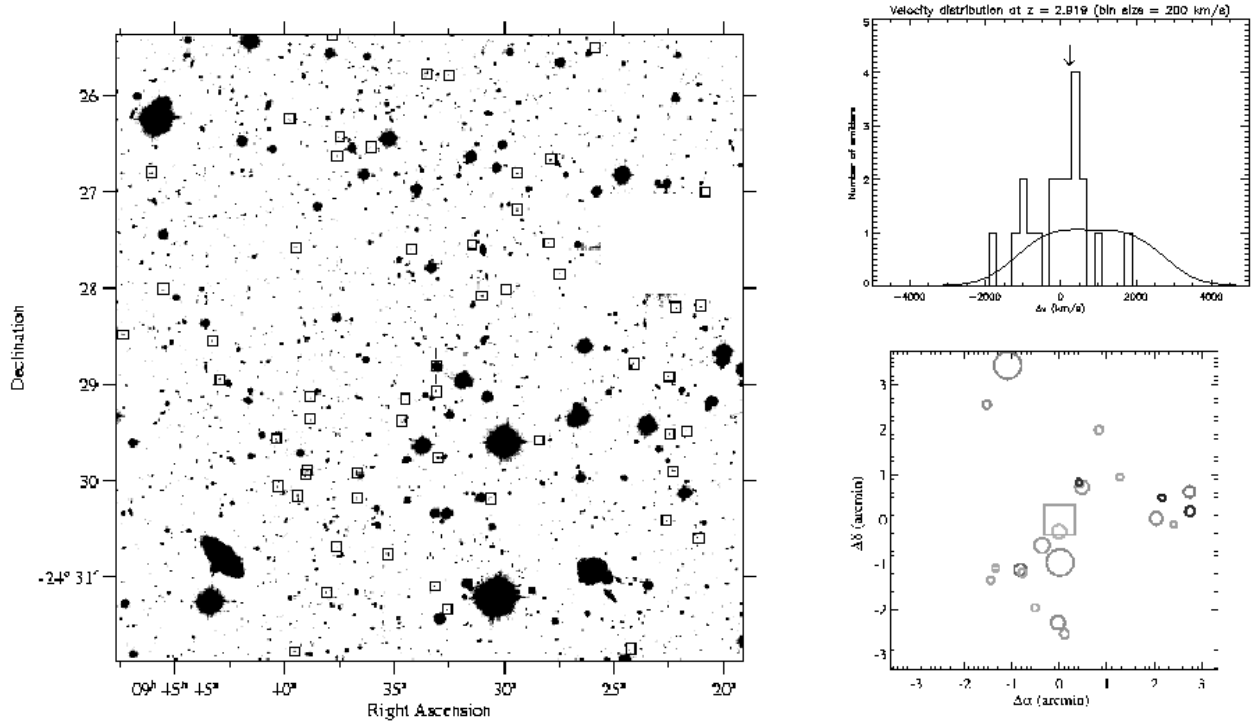


Figure 3. [Top Left] VLT narrow-band $\text{Ly}\alpha$ image[?] (grey scale; continuum not subtracted) of the $z = 2.919$ radio galaxy MRC 0943–242 with LaEG’s identified (open squares). The blank area near the NW corner was occulted by a slit because of a bright star. [Top Right] Histogram of the velocity distribution of the 18 LaEG’s + radio galaxy which were spectroscopically confirmed. [Bottom Right] Spatial distribution of the LaEG’s (circles) + radio galaxy (square). Circle diameters are proportional to $\text{Ly}\alpha$ flux and range from 0.8 and $17 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$.

3.2. TN J1338–1942 at $z = 4.102$

TN J1338–1942 was imaged using a narrow-band filter with a 60 \AA bandpass centered at the $z = 4.102$ redshifted $\text{Ly}\alpha$ line (6202 \AA) with the ESO VLT using the same telescope and instrument set up as for MRC 0943–242. The total exposure time was 33,300s, reaching a magnitude limit of $\text{NB}_{AB} = 27.4$ (3σ , $2.0''$ aperture) and the data were obtained during photometric conditions and $0.8''$ seeing. A broad-band B image ($B_{AB} = 27.02$, 3σ , $2''$ aperture) was used to identify LaEGs’s in the same manner as for MRC 0943–242. A total of 33 objects were identified as potential LaEG’s (excluding the radio galaxy itself), 28 of which were retained after rejecting 5 objects based on blue $B - R$ colors (see Ref. ? for details).

Multi-slit spectra of 23 LaEG candidates were obtained with the ESO FORS2 spectrograph using two masks and $\sim 33,300$ s exposures each. The observations, and Occam’s razor,[?] confirmed that 20 of the galaxies are at the redshift of TN J1338–1942 (Fig. 4). The velocity dispersion of the galaxies (326 km s^{-1}) is narrower than in the other, lower redshift proto-clusters (Table 2) and shows no evidence for substructure. The spatial distribution appears to be fairly random except that the radio galaxy itself, which is presumably the most massive galaxy, does *not* appear to be near the centroid of the proto-cluster.

3.3. Conclusions for proto-clusters

Narrow-band imaging of the fields around HzRGs provides a powerful method for finding proto-clusters over a large range of redshifts. LaEG’s represent only a small fraction (20 – 25%) of the total galaxy population in proto-clusters.[?] However, for faint galaxies ($I_{AB} > 25.5$) at high redshifts emission-line objects such as these may be the only ones for which redshifts may be measurable, even with 8 – 10m class telescopes.

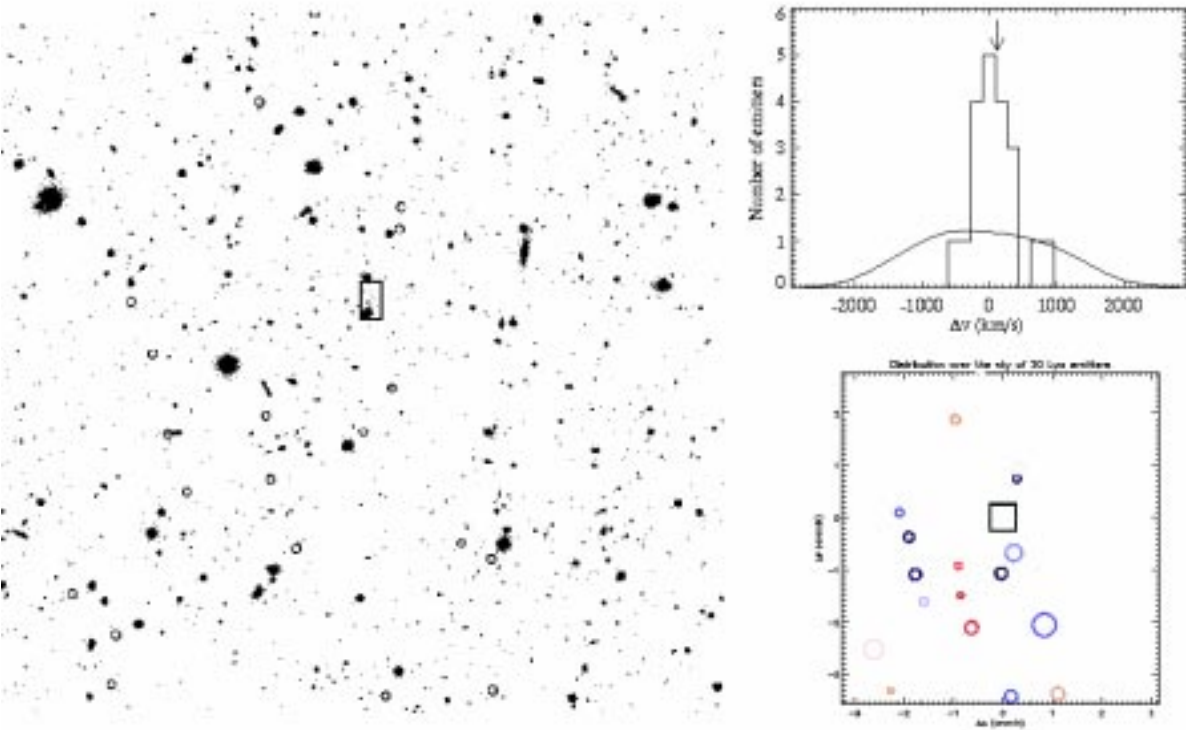


Figure 4. [Top Left] VLT narrow-band Ly α image[?] (grey scale; $6.4' \times 6.2'$) of TN J1338–1942 with 20 spectroscopically confirmed LaEG candidates identified (circles). [Top Right] Histogram of the velocity distribution of the LaEG's. [Bottom Right] Spatial distribution of the LaEG's (circles) + radio galaxy (square). Circle diameters are proportional to Ly α flux and range from 0.8 and $17 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$.

The mass function of galaxy clusters and groups depends strongly on cosmological parameters and evolves with lookback time.[?] Observations of HzRG proto-clusters will be very helpful in investigating cosmological models in that they may be used to determine the masses of galaxy clusters and groups at redshifts which can not be reached by other methods (X-ray selection, gravitational lensing), or which are prohibitive in observing time ('blind' multi-color surveys with no prior redshift information).

The over-densities in the HzRG proto-clusters are similar to that in the SSA22a over-dense region and lead to similar estimates of the cluster masses of $10^{14} - 10^{15} M_{\odot}$. In fact, the luminosity functions and lifetimes of luminous radio sources are consistent with *every* such over-dense field hosting a massive galaxy that will be an active radio source at least once in its lifetime.[?]

4. FUTURE WORK

Large 8 – 10m telescopes for the first time unlock the potential of narrow-band imaging as a *cosmological* tool. Giant emission-line nebulae are now known to exist out to $z \sim 4$, some with obvious ionizing sources, some without (Table 1). By studying their properties we may learn about the formation of galaxies, the feedback from AGN/starburst winds, and the chemical enrichment of intra-cluster media. Radio-loud galaxies seem endowed by rather spectacular nebulae, probably they are the most massive forming galaxies, but other types of objects need to be studied as well. For example, if quasars would become active during the very early stages of galaxy formation, then one might expect them to boost the Ly α emission in the surrounding gas, which might be used to learn more about the galaxy formation process.[?]

Emission-line imaging of the fields around targeted high redshift objects can push searches for galaxy proto-clusters to much higher redshifts than would otherwise be possible. Again radio galaxies are ideally suited for this because they live in the most massive galaxies which live in the most over-dense regions.

To fully exploit emission-line imaging as a cosmological tool will require large field-of-view (0.5×0.5 sq.deg) tunable filters,[?] Imaging Fourier Transform Spectrometers,[?] or other types of multi-wavelength ‘3-D’ imaging devices.[?] Large (> 200 cm²) custom made narrow-band filters are expensive, and it is an unfortunate fact that the largest telescopes also require the largest filters, even for modest sized fields of view (273 cm² for a 81 sq.arcmin FOV in the case of DEIMOS at Keck for example). This problem will be even more acute for the next generation of ‘extremely’ large telescopes such as the CELT 30m. It is also clear that the selection of emission-line objects provides only partial insight into the galaxy populations and kinematics of proto-clusters, and obtaining spectroscopic absorption line redshifts of faint galaxies will be very difficult. The most powerful observational tool here would again be a 3-D imaging device with selectable, medium sized (few 100Å wide) bandpasses so that accurate photometric redshift measurements can be made.

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